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Techno-economic evaluation of off-grid hybrid photovoltaic–diesel–battery power systems for rural electrification in Saudi Arabia—A way forward for sustainable development

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Abstract

The burning of depleting fossil fuels for power generation has detrimental impact on human life and climate. In view of this, renewable solar energy sources are being increasingly exploited to meet the energy needs. Moreover, solar photovoltaic (PV)–diesel hybrid system technology promises lot of opportunities in remote areas which are far from utility grid and are driven by diesel generators. Integration of PV systems with the diesel plants is being disseminated worldwide to reduce diesel fuel consumption and to minimize atmospheric pollution. The Kingdom of Saudi Arabia (K.S.A.) being endowed with high intensity of solar radiation, is a prospective candidate for deployment of PV systems. Also, K.S.A. has large number of remote scattered villages. The aim of this study is to analyze solar radiation data of Rafha, K.S.A., to assess the techno-economic feasibility of hybrid PV–diesel–battery power systems to meet the load requirements of a typical remote village Rawdhat Bin Habbas (RBH) with annual electrical energy demand of 15,943 MWh. Rafha is located near RBH. The monthly average daily global solar radiation ranges from 3.04 to 7.3 kWh/m^2. NREL's HOMER software has been used to perform the techno-economic evaluation. The simulation results indicate that for a hybrid system composed of 2.5 MWp capacity PV system together with 4.5 MW diesel system (three 1.5 MW units) and a battery storage of 1 h of autonomy (equivalent to 1 h of average load), the PV penetration is 27%. The cost of generating energy (COE, US$/kWh) from the above hybrid system has been found to be 0.170$/kWh (assuming diesel fuel price of 0.1$/l). The study exhibits that the operational hours of diesel generators decrease with increase in PV capacity. The investigation also examines the effect of PV/battery penetration on COE, operational hours of diesel gensets. Concurrently, emphasis has been placed on: un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (for different scenarios such as: PV–diesel without storage, PV–diesel with storage, as compared to diesel-only situation), COE of different hybrid systems, etc. The decrease in carbon emissions by using the above hybrid system is about 24% as compared to the diesel-only scenario.

Keywords: Solar radiation; PV; Battery; Rural/village electrification; Diesel generators; Carbon emissions

Contents

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1. Introduction

Presently, about two billion people worldwide living in small remote villages which are far from utility grid lack access to electricity. In many cases, utility grid extension is impractical owing to dispersed population or rugged terrain, thus stand-alone power systems are likely to be the most viable options. Various combinations of renewable energy sources (such as wind, solar PV, etc.) and diesel generators with/without rechargeable batteries are currently being researched (for electricity production) and are marketed as cost-effective and ecologically sound solutions in a long run. In this context, one of the options to provide electricity to remote locations is by utilization of indigenous solar energy (one of the potential market for PV installations is in remote areas) together with existing diesel gensets [1]. Such systems are referred to as remote hybrid power systems. Also, hybrid system shields the increasing oil price-risk and minimizes unprecedented environmental damage due to burning of finite/fixed/depleting fossil fuels. The last decade has brought with it rapid expansion in the use of renewable energy sources for displacement of oil-produced energy, and eventually to reduce atmospheric degradation. Additionally, to comply with December 1997s Kyoto's protocol on climate change (due to carbon emissions), about 160 nations have reached a first ever agreement (to turn to renewable/wind/PV power) to limit carbon emission which is the principal cause of global warming.

Solar energy is one of the in-exhaustible, site-dependent, benign (does not produce emissions that contribute to the greenhouse effect), and potential source of renewable energy options that is being pursued by a number of countries with monthly average daily solar radiation in the range of 3–6 kWh/m^2, in an effort to reduce their dependence on fossil-based non-renewable fuels [2–9]. Solar collectors can be classified as either solar to thermal energy converters or solar to electric energy converters. Devices that directly convert solar into electric energy are called photovoltaics [7]. Currently thousands of PV-based power systems are being deployed worldwide, for providing power to small, remote, grid-independent or stand-alone applications [2]. Since K.S.A. is endowed with high solar radiation level, a fraction of its energy needs may be tapped from solar energy. Moreover, the use of solar energy reduces combustion of fossil fuels and the consequent CO_2 emission [10–13]. Although, solar energy is enormous, but PV driven power system is still an expensive option. However, PV finds application in remote areas where it is un-economical to stretch the utility grid [14,15]. PV cells have the advantage of minimum maintenance and easy expansion to meet growing energy needs. PV modularity (modules are available off-the-shelf) allows the users to tailor PV system capacity to the desired situation. PV systems produce electricity during the times when we demand it most, on hot sunny days coinciding with our peak electricity consuming periods. The demerits are: PV is cost-intensive and its sunshine-dependent output does not match the load on 24-h basis. However, major technological strides (yielding cost reduction, improved efficiency, etc.) may change the scenario [6,14].

A PV system alone cannot satisfy load on a 24-h basis [14]. Stand-alone diesel gensets are generally expensive to operate and maintain especially at low load levels [16]. Often, the variations of solar energy generation do not match the time distribution of the demand. Therefore power generation systems recommend the association of battery storage facility to smoothen the time distribution mismatch between the load and solar energy generation and to account for maintenance of the systems [6,17]. Use of diesel system with PV–battery reduces battery storage requirement. Research carried out in other parts of the world indicate that hybrid combination of PV–diesel–battery systems is a reliable source of electricity [15]. PV and diesel have complementary characteristics: capital cost of PV is high as compared to diesel, operating cost of PV is low (relative to diesel), maintenance requirements of PV are less as compared to diesel, diesel energy is available all the time where as availability of PV is highly dependent on solar radiation [15]. In simple system, the diesel runs continuously (with some minimum load requirement) to cover the difference between PV power and load demand. Obviously, the diesel will run under part-load or no-load conditions. Due to low efficiency of the diesel generator at low load, the fuel saving potential in these systems is limited (diesel generator efficiency drops tremendously when it operates at less than 40% of full load). Fuel economy considerations indicate that the diesel should be stopped when the average power of the PV, relative to the load, is high. This intermittent operation results in high start–stop cycling frequency (this promotes wear of the diesel system and hence increases demand for maintenance). Also a system without storage must maintain enough spinning reserve to cover all possible sudden net load peaks due to village load peaks and/or PV power drops. In this regard, researchers advocate that incorporation of a short-term battery storage into PV–diesel system yields the following: may further elevate the fuel saving potential (as compared to diesel-only, or PV–diesel scenario), may further smoothen the fluctuations in the power output, may further reduce operational hours of diesel system, may reduce the excess energy generated. For a given level of PV penetration, the lower the excess energy the better the economics of the PV–diesel system. The prospect of hybrid PV–diesel systems has gained momentum and number of PV–diesel–battery installations exist around the world [15,18,19]. The cumulative installed capacity of all solar systems deployed around the world passed the landmark figure of 3120 MWp in 2003. The global installed capacity of solar power is expected to reach 207 GWp by 2020 (the cost of solar modules is likely to go down to 1US$/W delivered). Also, the projections indicate that by 2020 solar systems can provide energy to over a billion people globally and provide 2.3 million full-time jobs [20].

Since last two decades, K.S.A.'s electricity sector has grown remarkably. The number of consumers grew from 300,000 in early 1970 to approximately 4.2 million in 2003. The installed generating capacity of the power plants reached more than 35,000 MW in 2005 [21–23]. Population growth and industrialization are increasing the demand (5–7% per annum) for electricity, which is expected to reach about 55,000 MW by

2020. The needs in the Kingdom's transmission and distribution expansion are equally daunting. Although currently Saudi Arabia has about 210,000 miles of transmission network, the creation of a unified national grid will require more than 32,000 km of additional lines. The K.S.A.'s area is large, with large number of settlements (far from electric grids) scattered all over the Kingdom. The supply of electricity to these remote villages through diesel generators alone or by connecting into the nearest grid can be an expensive option in a long run. In the light of these problems, attention is being focussed on feasibility of utilizing of hybrid PV–diesel–battery power systems for providing electricity to remote villages. The retrofitting of PV systems along with the existing diesel stations may result in reduced fuel transport/storage/consumption, lower diesel emissions, fewer diesel spills, and possibly longer engine life.

The research on feasibility of renewable energy systems at Saudi Arabia, has been the subject matter of several earlier studies [24–26]. The objective of this study is to analyze solar radiation data (of the period 1971–1980) of Rafha (29°38′N, 43°29′E, northeast, K.S.A.), to assess the technical and economic feasibility of hybrid PV–diesel–battery power systems to meet the load requirements of a typical remote village Rawdhat Bin Habbas (RBH) with annual electrical energy demand of 15,943 MWh (of the year 2003). Rafha is located near RBH. The hybrid systems simulated consist of different combinations of PV panels/sizes supplemented with battery storage and diesel generators. The study investigates the feasibility of utilizing solar/PV energy to meet the load requirements of the remote village in conjunction with the diesel generators. Specifically, the merit of hybrid PV–diesel–battery system has been evaluated with regards to its size, operational requirements, cost, etc. National Renewable Energy Laboratory's (NREL) HOMER software has been used to perform the techno-economic feasibility of hybrid PV–diesel–battery power systems. HOMER is a tool or computer model that facilitates design of stand-alone electric power systems [27]. The village has about 10,000 inhabitants. Currently, the load requirements of the village are met by a diesel system of 6.72 MW capacity. The investigation demonstrates the impact of PV penetration and battery storage on: energy production, cost of energy, number of operational hours of diesel gensets for a given hybrid configuration, etc. Emphasis has also been placed on un-met load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (relative to diesel-only scenario) of different hybrid systems, cost of PV–diesel–battery systems, COE of different hybrid systems, etc.

2. Background information

Climatic conditions determine the availability of solar energy at a given site. In other words, availability of solar PV power is influenced by topography and weather conditions at a site. Rafha is located just in the northeast of Saudi Arabia. The overall mean temperature is about 34 °C. The relative humidity exhibits a large diurnal cycle on the order of 34% round the year. The overall mean air density is about 1.13 kg/m^3. The overall (long-term) mean value of wind speed is 3.44 m/s at 10 m height, while the maximum has been found to be 20.03 m/s. The winds blow from 270° to 360° direction range (north to north-westerly winds) for most of the time during the year. Long-term mean wind direction is about 340°.

3. Solar radiation data and operational strategy of hybrid system

Long-term monthly average daily (of the period 1971–1980) global solar radiation data of Rafha is plotted in Fig. 1 [28]. The irradiation level is high during the summer months (May–August) as compared to other months. The yearly average daily solar radiation is about 5.32 kWh/m^2. The above long-term average data has been used for simulations in HOMER. The energy calculations are made by matching the solar radiation data with the characteristics of PV modules [29]. The characteristics of some of the commercial PV modules are furnished in Table 1. The PV modules which are composed of several solar cells are integrated to form solar arrays. Despite advancements in the state-of-the-art, today's best PV systems can achieve an overall efficiency of about 12% [7].

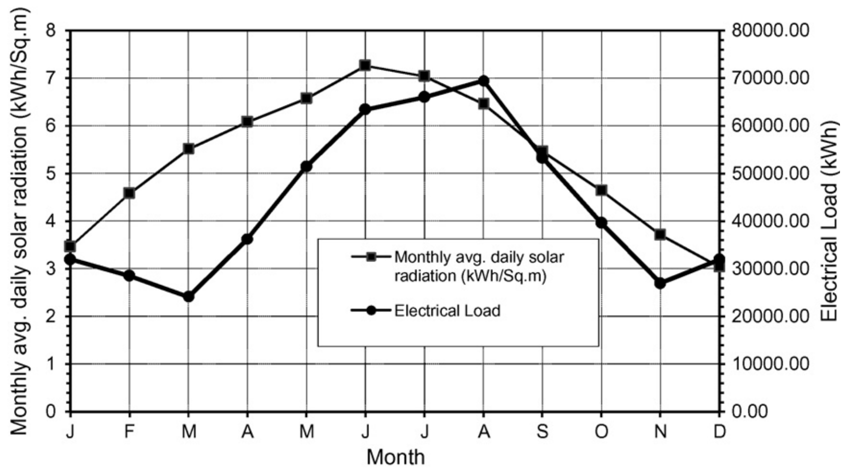


Fig. 1. Monthly average daily global solar radiation (long-term average) and monthly average daily load at a remote village of Saudi Arabia.

Table 1
Characteristics of some commercial PV modules

Module size, $L \times W \times D$	Rated power, Rp (W)	Current (A)	Voltage (V)	Module reference, η
1113 mm × 502 mm × 50 mm	60	3.5	17.1	0.107
1108 mm × 660 mm × 50 mm	83	4.85	17.1	0.113
18.5 in. × 25.7 in. × 2.1 in.	35	2.33	15.0	0.15
25.2 in. × 25.7 in. × 2.1 in.	50	3.00	16.7	0.15
34.1 in. × 25.7 in. × 2.2 in.	70	4.14	16.9	0.15
56.1 in. × 25.7 in. × 2.2 in.	120	7.10	16.9	0.15
50.8 in. × 39.0 in. × 1.4 in.	167	7.2	23.2	0.15

L: length; *W*: width; *D*: depth. The above modules are High Efficiency Solar Electric Modules and Kyocerasolar Modules. Power specifications are at standard test conditions of 1000 W/m^2 solar irradiance, 25 °C cell temperature.

The solar insolation varies not only during different seasons but also at different times of the day. Therefore, for applications where energy is required for a 24-h period, the need cannot be met through a PV system alone. In this connection, integration of PV installations with battery storage or diesel system or with both, can meet the required load distribution on a 24-h basis. This type of coupling also avoids oversizing/undersizing of the major components of hybrid system.

The architecture of hybrid PV–diesel–battery system is shown in Fig. 2. The dispatch strategy is load following type. The operation strategy is as follows: in normal operation, PV feeds the load. The excess energy (the energy above the average hourly demand; if any) from PV is stored in the battery until full capacity of the storage system is reached. The main purpose of introducing battery storage is to import/export energy depending upon the situation. In the event, that the output from PV exceeds the load demand and the battery's state of charge is maximum, then the excess energy is fed to some dump load or goes un-used (due to lack of demand). A diesel system is brought online at times when PV fails to satisfy the load and when the battery storage is depleted.

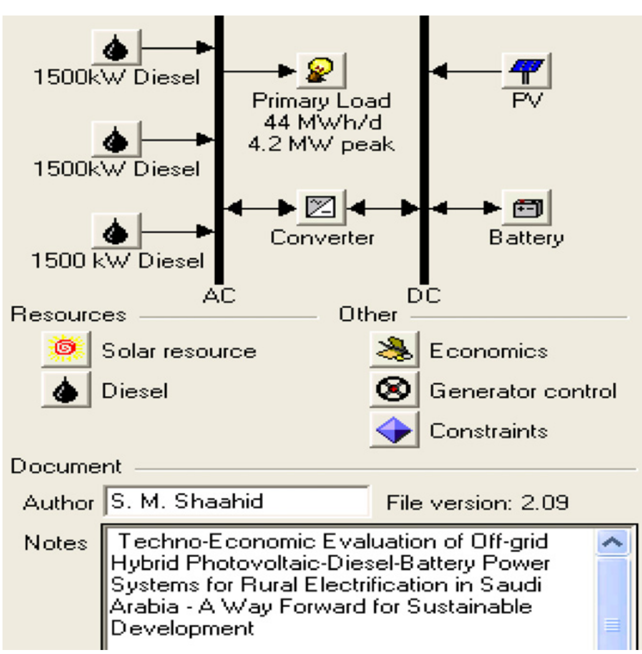


Fig. 2. Schematic of hybrid PV–diesel–battery power system.

4. Results and discussions

An important element of any power generating system is load. Load has pronounced effect on system design. As a case study, the measured annual average electric energy consumption of a typical remote village with annual electrical energy demand of 15,943 MWh (minimum load = 500 kW, maximum load = 4230 kW, average load = 1820 kW) has been considered as yearly load in the present study. This load could also be a representation of many other remotely located settlements of the K.S.A. which are far from the utility grid. The projected monthly average daily electrical energy consumption (of 2003) is shown in Fig. 1. As depicted in Fig. 1, the load seems to peak during June to September. The raw electrical load data for a complete year (2003) is presented in Fig. 3. Currently, the load requirements of the village are met by a diesel system of 6.72 MW installed capacity.

The selection and sizing of components of hybrid power system has been done using NREL's HOMER (Hybrid Optimization Model for Electric Renewables) software. HOMER is a general-purpose hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes: electrical loads (load data), renewable resources (e.g. solar radiation data), component technical details/costs, constraints, controls, type of dispatch strategy, etc. HOMER designs a optimal power system to serve the desired loads. HOMER is an simplified optimization model, which performs hundreds or thousands of hourly simulations (to ensure best possible matching between supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. The software performs automatic sensitivity analyses to account for the sensitivity of the system design to key parameters, such as the resource availability or component costs [27].

The hybrid systems simulated in the present investigation consist of different combinations of PV panels supplemented with battery bank and diesel generators. The study explores a suitable mix of key parameters such as: PV array power (kWp), battery storage, and diesel capacity to match the pre-defined load (with 0% capacity shortage). HOMER allows use of three diesel units for simulation of hybrid systems. Diesel generators are generally sized to meet the peak demand of the power. The peak demand of the village is about 4.23 MW. In this regard,

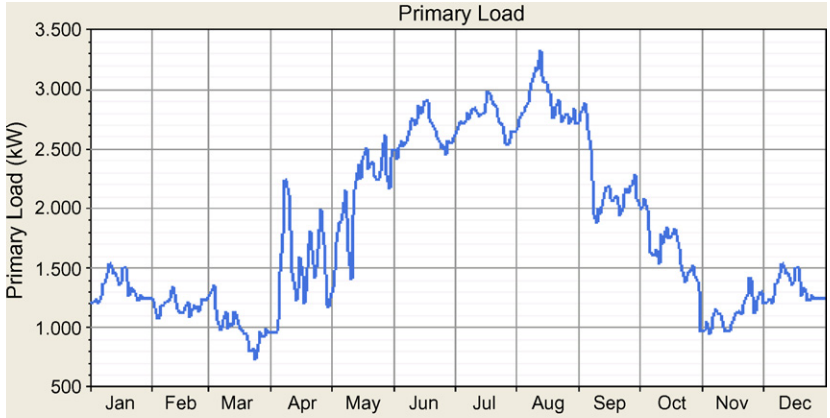


Fig. 3. Daily average load (kW) of the remote village.

three diesel generators each of 1.5 MW capacity (to cover peak load, to cover spinning reserve of about 7% to overcome rapid changes in load) have been considered for carrying out the technical and economic analysis of the hybrid systems. The operating/spinning reserve is surplus electrical generation capacity (over and above that required to serve the load) that is instantly available to serve additional loads. It provides reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations for various scenarios have been made by considering different PV capacities. The PV capacity has been allowed to vary from 0 to 6 MW. The battery storage/bank sizes (kWh) considered are 0–100 load min/autonomy (equivalent to 0–100 min of average load, i.e. equivalent to 0–730 Surette batteries with details as mentioned in Table 2). The study assumptions made for making simulations on HOMER are tabulated in Table 2. As a starting point, simulations have been performed for PV–diesel systems with no-storage. The simulation results (for diesel price of 0.1US$/l) are presented in Fig. 4. In Fig. 4, first column shows the presence of PV modules in hybrid system, second–fourth column indicate the presence of diesel units, sixth column highlights size/capacity (kW) of PV considered in a given case, 13th column shows cost of energy generation (COE, US$/kWh), etc. It can be noticed from these results that in general the PV penetration (renewable energy fraction, column 14) has varied from 0 to 50%. In an isolated system, renewable energy contribution of 50% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage and frequency. The level of renewable energy penetration in hybrid systems (deployed around the world) is generally in the range of 11–25% [15]. A trade-off need to be established between different available options. The COE from hybrid PV–diesel system (2.5 MW PV, 4.5 MW diesel system, no-storage, 0% annual

Table 2
Technical data and study assumptions of PV, diesel units, and batteries

Description	Data
PV	
Capital cost	6900US$/kW
Life time	25 years
Operation and maintenance cost	0US$/year
Diesel generator units (three units with following details)	
Rated power of each diesel unit 1 (D1, D2, D3)	1500 kW
Minimum allowed power (min load ratio)	40% of rated power
Operation and maintenance cost	3.01US$/h
No-load fuel consumption	126.2 l/h
Full load fuel consumption	495.2 l/h
Overhaul period	43,800 h
Batteries	
Type of batteries	Surette 6CS25P
Nominal voltage (V)	6 V
Nominal capacity	1156 Ah
State of charge (SOC)	40%
Nominal energy capacity of each battery (V Ah/1000)	6.94 kWh
Operation and maintenance cost	50$/year
Dispatch/operating strategy	Multiple diesel load following
Spinning reserve	
Additional online diesel capacity (to guard against increases in the load or decreases in the PV power output)	7% of the load

PV (kW)	D1500 (kW)	D1500 (kW)	D1500 (kW)	Conv. (kW)	Total Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D1500 (hrs)	D1500 (hrs)	D1500 (hrs)
	1500	1500	1500		$ 816,000	$ 8,171,198	0.048	0.00	5,903,...	8,760	5,539	1,397
500	1500	1500	1500	1500	$ 6,141,000	$ 14,210,329	0.083	0.06	5,644,...	8,760	5,276	1,246
1000	1500	1500	1500	1500	$ 9,591,000	$ 17,766,764	0.104	0.12	5,424,...	8,760	5,119	1,072
1500	1500	1500	1500	1500	$ 13,041,...	$ 21,368,354	0.126	0.17	5,245,...	8,742	4,973	941
2000	1500	1500	1500	1500	$ 16,491,...	$ 24,959,166	0.147	0.22	5,064,...	8,594	4,831	845
2500	1500	1500	1500	1500	$ 19,941,...	$ 28,564,778	0.168	0.27	4,901,...	8,364	4,715	763
3000	1500	1500	1500	1500	$ 23,391,...	$ 32,217,432	0.189	0.31	4,777,...	8,173	4,621	695
3500	1500	1500	1500	1500	$ 26,841,...	$ 35,916,052	0.211	0.35	4,689,...	8,046	4,549	641
4000	1500	1500	1500	1500	$ 30,291,...	$ 39,638,588	0.233	0.39	4,620,...	7,936	4,492	611
4500	1500	1500	1500	1500	$ 33,741,...	$ 43,381,688	0.255	0.42	4,566,...	7,854	4,448	593
5000	1500	1500	1500	1500	$ 37,191,...	$ 47,140,484	0.277	0.45	4,524,...	7,796	4,408	581
5500	1500	1500	1500	1500	$ 40,641,...	$ 50,904,264	0.299	0.47	4,486,...	7,729	4,382	575
6000	1500	1500	1500	1500	$ 44,091,...	$ 54,675,088	0.321	0.50	4,455,...	7,681	4,345	566

Fig. 4. Technical and economic parameters of PV–diesel systems.

capacity shortage) with 27% PV penetration has been found to be is 0.168US$/kWh as shown in Fig. 4. It can be depicted from Fig. 4, that COE increases with increase in penetration of PV. Literature indicates that COE from PV systems in general is about 0.20US$/kWh [30–33].

It is also evident from Fig. 4, that as penetration of PV increases, the operational hours of diesel generators decrease which eventually reduce emission of greenhouse gases. It can be noticed that for diesel-only situation, the operational hours of the three diesel units are 8760, 5539, and 1397, respectively. However, for hybrid PV–diesel system (2.5 MW PV, 4.5 MW diesel system, 0% annual capacity shortage, zero battery storage, Fig. 4) with 27% PV penetration, the operational hours of the three diesel units are 8364, 4715, and 763, respectively. This clearly reflects that operational hours of the three 1500 kW diesel generators of hybrid PV–diesel (27% PV penetration) system decrease by 5%, 15%, and 45%, respectively as compared to diesel-only (0% PV) situation. This indicates that with introduction of PV machines, load on the second and third diesel generators has decreased considerably.

For a given PV capacity of 2.5 MW (together with 4.5 MW diesel system), the details related to energy generated by PV and diesel systems, excess electricity, un-met load (kWh), capacity shortage (kWh) and the cost break-down of PV–diesel power systems are presented in Figs. 5 and 6. It can be seen from Fig. 5 that with the above system configuration, un-met load is 0 kWh and excess energy of about 7% is generated. It should be mentioned over here, that this excess energy produced goes un-used due to lack of demand (sometimes provision is made to provide this excess energy to dump loads). Fig. 5 indicates that monthly average hybrid PV–diesel generated power is high during summer months (May–August) as compared to other months. This is a favorable characteristic because electricity demand is high during the summer months in K.S.A. HOMER hybrid model indicates that the total initial capital cost of the hybrid system (2.5, 4.5 MW, no-storage) is US$ 19,941,000 while the net present cost (NPC) is US$ 28,561,716 (Figs. 5 and 6). It can be noticed from (Fig. 6) that the initial capital cost of PV system is about 84% of the total initial capital cost. This indicates that initial cost of PV system in hybrid system is dominant. Regarding annual operation and maintenance cost of PV/converter system, it is about 3% of the total O & M + fuel cost and the O & M + fuel cost of the diesel system is about 97%.

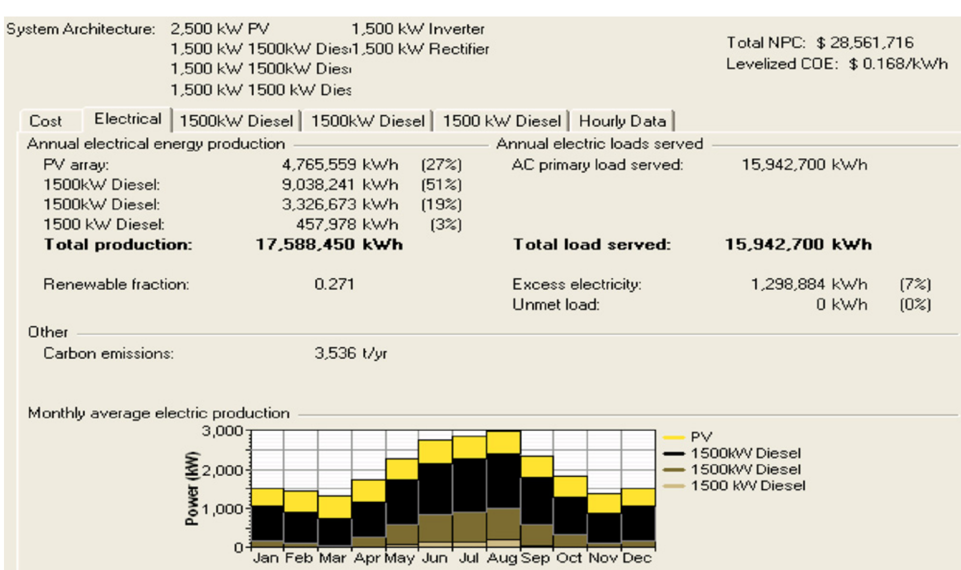
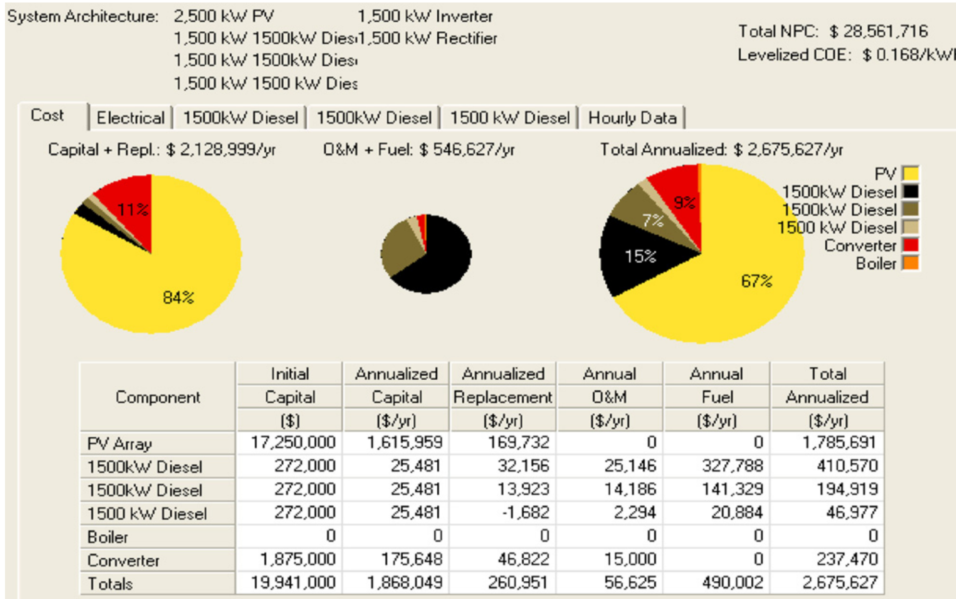


Fig. 5. Power generated by photovoltaic and diesel systems.



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	17,250,000	1,615,959	169,732	0	0	1,785,691
1500kW Diesel	272,000	25,481	32,156	25,146	327,788	410,570
1500kW Diesel	272,000	25,481	13,923	14,186	141,329	194,919
1500 kW Diesel	272,000	25,481	-1,682	2,294	20,884	46,977
Boiler	0	0	0	0	0	0
Converter	1,875,000	175,648	46,822	15,000	0	237,470
Totals	19,941,000	1,868,049	260,951	56,625	490,002	2,675,627

Fig. 6. Cost of photovoltaic and diesel power systems.

Table 3
Number of operational hours of diesel generators, PV penetration, un-met load, excess energy, annual diesel fuel consumption, cost of energy of hybrid PV–diesel systems (for given PV/diesel capacity, for different sizes of battery storage capacity, based on diesel price of 0.1US$/l)

Hybrid system (kW)	Battery storage capacity (minutes of average hourly demand)	Operational hours of the three diesel generators (each of 1.5 MW capacity)			Renewable energy (PV) fraction (% of load)	Un-met load (kWh)	Excess energy (%)	Carbon emissions (tons/year)	Annual diesel fuel consumption (l/year)	Cost of energy, COE ($/kWh)
		D1	D2	D3						
0 kW PV + 4.5 MW diesel	0	8760	5539	1397	0	0	0	4260	5,903,541	0.048
2.5 MW PV + 4.5 MW diesel	0	8354	4713	762	27	0	7	3536	4.900,021	0.168
	10	8259	4307	570	27	0	7	3462	4,797,325	0.168
	20	8155	3964	373	27	0	7	3391	4,698,696	0.168
	30	8063	3735	230	27	0	6	3335	4,621,684	0.168
	40	7971	3596	157	27	0	6	3294	4,565,531	0.169
	50	7905	3531	113	27	0	5	3270	4,531,446	0.169
	60	7862	3495	89	27	0	5	3255	4,510,841	0.170
	70	7841	3485	72	27	0	5	3248	4,500,975	0.171
	80	7833	3479	68	27	0	5	3245	4,497,260	0.172
	90	7832	3474	68	27	0	5	3244	4,496,231	0.173
	100	7830	3474	68	27	0	5	3244	4,495,684	0.174

The percentage of fuel savings by using hybrid system (2.5 MW PV, 4.5 MW diesel system) as compared to the diesel-only case is about 17% as shown in Fig. 4. Moreover, percentage fuel savings increases by increasing the PV capacity. The diesel fuel savings may only be quantifiable by means of justifying the additional capital expenditure invested in PV. It has also been observed that the carbon emissions for diesel-only situation are 4260 tons/year. However, with PV–diesel hybrid system (2.5 MW PV, 4.5 MW diesel system) the carbon emissions are 3536 tons/year (Fig. 5). This reflects that the percentage decrease in carbon emissions with 27% PV penetration is about 17% as compared to diesel-only (0% PV energy) case. This implies about 724 tons/year of carbon emissions can avoided entering into the local atmosphere with 27% PV penetration.

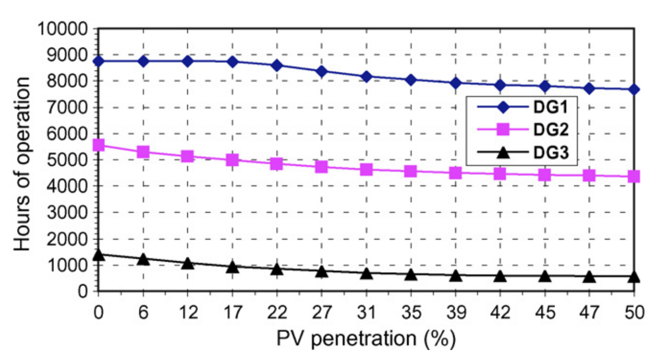


Fig. 7. Impact of PV penetration on diesel engine operation time.

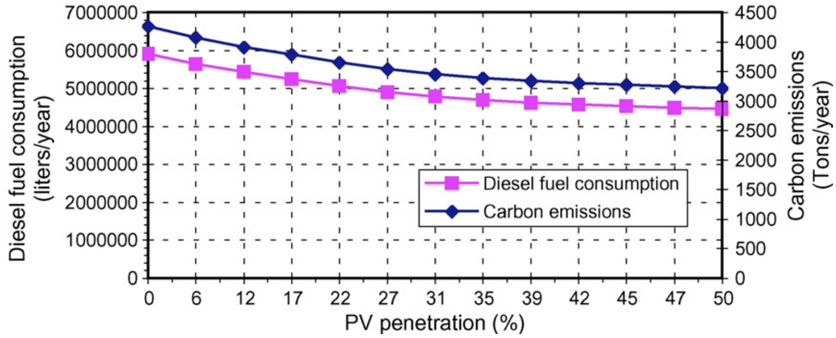


Fig. 8. Impact of PV penetration on diesel fuel consumption and carbon emissions.

As a final remark, attempt has been made to explore the benefits of incorporation of short-term storage (in PV–diesel systems) in terms of fuel savings, diesel run time, and excess energy generation relative to no-storage systems. In order to assess the impact of battery storage in a given hybrid system (2.5 MW PV, 4.5 MW diesel, 27% PV penetration), battery storage capacity was varied from 0 to 100 load min/autonomy (equivalent to 0–100 min of average load). The results of the above simulation are presented in Table 3 which demonstrates the effect of battery storage on operational hours of diesel units, diesel fuel consumption, excess energy generation, carbon emissions, COE, etc. The COE from the above hybrid PV–diesel–battery system (27% PV penetration) with 60 min of autonomy (60 min of average load) has been found to be 0.170\$/kWh (assuming diesel fuel price of 0.1\$/l). Literature indicates that COE from PV systems is about 0.20US\$/kWh. As mentioned above, percentage fuel savings by using hybrid PV–diesel system (2.5 MW PV, 4.5 MW diesel system, no-storage) is 17% as compared to diesel-only situation. Expectedly, presence of battery further enhances the fuel saving potential. The percentage fuel savings for the same PV penetration is 27% (8% extra relative to PV–diesel system) with inclusion of 1 h of battery storage. Further increase in storage results in only little economic benefits because of high cost of batteries (i.e. fuel saving is not much for battery storage greater than 1 h of average load). Broadly speaking, maximum benefits of storage (in the present case) can be realized for a battery capacity of 60 min of autonomy (average load). As stated earlier, the percentage decrease in carbon emissions by using hybrid system (2.5 MW, 4.5 MW diesel system, no-storage, 27% PV penetration) as compared to the diesel-only scenario is 17%. However, the percentage decrease in carbon emissions for the same PV penetration is 24% (as compared to diesel-only case) with inclusion of 1 h of battery storage. It can be noticed that the COE increases with increase in size of battery storage. Also, the number of operational hours (diesel run time) of the diesel units in PV–diesel system further decreases with inclusion of battery storage (Table 3). For example, for the above hybrid PV–diesel (2.5 MW PV, 4.5 MW diesel system, 27% PV penetration, no-storage) system, the operational hours of the three 1500 kW diesel generators of hybrid PV–diesel (27% PV penetration) system decrease by 5%, 15%, and 45%, respectively as compared to diesel-only (0% PV) situation.

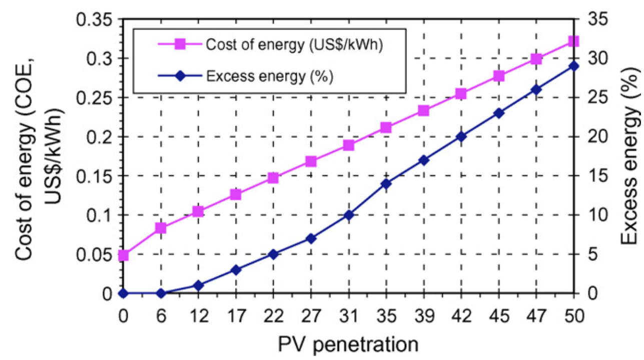


Fig. 9. Impact of PV penetration on COE and excess energy generated.

However (for the same configuration) with inclusion of 60 load min of battery, the operational hours of the three 1500 kW diesel generators of hybrid PV–diesel (27% PV penetration) system decrease by 10%, 37%, and 94%, respectively as compared to diesel-only (0% PV) situation. In addition to the above benefits, presence of short-term storage also results in decrease in excess energy. The excess energy is 7% for hybrid PV–diesel (2.5 MW PV, 4.5 MW diesel system, 27% PV penetration, no-storage) system. However (for the same configuration) with inclusion of 1 h of battery, the excess energy is 5% for hybrid PV–diesel–battery scenario. For a given level of PV, the lower the excess energy the better the economics of the PV–diesel systems. The effect of PV penetration on diesel operation time, diesel fuel consumption, carbon emissions, excess energy generation, etc., is demonstrated more explicity in Figs. 7–9.

5. Concluding remarks

The study indicates that the location being blessed with considerable monthly average daily global solar radiation intensity (3.04–7.3 kWh/m^2), is a prospective candidate for deployment of PV power systems. The simulation results indicate that for a hybrid system composed of 2.5 MWp PV system together with 4.5 MW diesel system and a battery storage of 60 min of autonomy (equivalent to 1 h of average load), the PV penetration is 27%. The cost of generating energy (COE) from the above hybrid PV–diesel–battery system has

been found to be 0.170US$/kWh (assuming diesel fuel price of 0.1$/l). The study exhibits that for a given hybrid configuration, the number of operational hours of diesel generators decreases with increase in PV capacity. It has been found that the for a given PV–diesel hybrid system, the decrease in diesel run time is further enhanced by inclusion of battery storage. The percentage fuel savings by using hybrid PV–diesel–battery system (2.5 MW PV, 4.5 MW diesel system, 1 h storage, 27% PV penetration) is 27% as compared to diesel-only situation. The percentage decrease in carbon emissions by using the above hybrid system has been found to be 24% as compared to the diesel-only scenario. More importantly, with the use of the above hybrid system, about 1005 tons/year of carbon emissions can be avoided entering into the local atmosphere.

The hybrid PV–battery–diesel configuration (by virtue of a high degree of flexibility) offers several advantages such as: diesel efficiency can be maximised; diesel maintenance can be minimized; and a reduction in the capacities of diesel and battery (while matching the peak loads) can occur. The present investigation shows that the potential of renewable energy option of solar energy cannot be overlooked. A fraction of Saudi Arabia's energy demand may be harnessed by deployment of PV systems. The observations of this study can be employed as a benchmark in designing/sizing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions. Over dependence on fossil fuels is alarming. Hence, investments in solar energy are imperative to mitigate energy crisis in foreseeable future.

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